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UNCERTAINTIES IN FAN PRESSURIZATION MEASUREMENTS

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ASTM Standard E779 is a test method for measuring the air tightness of building envelopes using fan pressurization.Uncertainty is introduced in the process from the uncertainty of the air flow and pressure measurements as well as from non-linearities in the system to be measured. This paper will analyze the precision and bias associated with making a measurement using E779 in typical field situations. Model specification (or modelization) errors may also contribute significantly to the overall uncertainty in the estimates of the 4 Pa leakage; the sources and sizes of these modelization errors interact with the instrumentation errors in making a fan pressurization test. Insufficient field data exists to fully include the effects of modelization and other low pressure phenomena, but the current standard can nevertheless be improved by tightening the instrumentations and procedural specifications and by judicious choice of pressure measurement stations.

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INTRODUCTION

Whole building air leakage is an important property of residential buildings. It serves both as a quality control indicator of the air tightness of the structure and as a quantitative measure for estimating the ventilation rate for both energy use and indoor air quality purposes. Although airflow at 50 Pa is the most used measure of air tightness, the most common *quantitative* application of air leakage measurement is the *Effective Leakage Area* ***(ELA)***. Various infiltration models such as the LBL[1.] infiltration model [2.] use leakage data in this form. Various ASHRAE Standards such as Standard 119 for Air Tightness[3.]and the standard 136 on estimation of air change rates for indoor air quality purposes [4.]] rely on the ELA concept also.

ASTM Standard E779 [5.] is a test method for determining the air leakage of the building envelope using fan pressurization. The test method requires that a set of air flow measurements be taken over a specified pressure range, from which a flow coefficient and exponent are calculated. Some infiltration models such as the AIM2 model [6.] use these parameters directly. This parameterization allows extrapolation of the flow to pressures lower than that of the measurements. ELA is calculated from the flow rate at 4 Pa and can be calculated directly from the flow coefficient and exponent.

It is important to understand that the usefulness of a measured quantity is dependent upon the certainty at which we know its true value. In the E779 procedure there are three categories of error which can increase our uncertainty: precision errors due to noise and other random errors, biases in the measurement of pressure and flow, and extrapolation errors. Although some bias and precision limits are included in the current standard, E779 does not contain a thorough treatment of these three categories of uncertainty.

It is impossible to quantify uncertainty without first specifying the quantity for which the uncertainty is desired. Similarly an optimal measurement protocol for measuring the air flow through the building envelope cannot be done without specifying the reference pressure. The focus of this report will be on estimating the uncertainty of the flow estimation at 4 Pa (and, hence, the ELA) implicit in the ASTM procedure and on examining alternative measurement techniques for improving the estimate.

The intent of this report is to evaluate different standards and protocols for measuring ELA from a general perspective, not to find the best set of procedures for a particular piece of instrumentation hardware. Although the general properties of fan pressurization equipment will be considered, it will be assumed that the hardware could be produced to meet the various specifications considered. For example, it will be assumed that the air flow capacity of the equipment will be optimally sized to meet the error specifications. Although it will not be done herein, the equations developed could be used to do a detailed analysis of a specific set of instrumentation under various protocols.

This report assumes that the reader is generally familiar with the art of making fan pressurization measurements (using a “Blower Door”) and standard E779. Both technical [7.]and popular[8.],[9.] articles are available to familiarize the reader with some of the relevant issues.

SOURCES OF ERROR

Before discussing the sources of error in the experiment it is important to define certain terms related to measurement uncertainty. **Accuracy** is the ability of a particular measurement to approach some exogenously chosen reference level (usually the *true* value); it is quantified by the total **measurement error**. One’s *estimate* of the measurement error is called the **measurement uncertainty.** The measurement error is made up of the precision error and the bias error. **Precision** is the property of reproducibility in a measurement; the precision error can be estimated from the standard deviation of a sample of repeated measurements. **Bias** errors are caused by systematic departures from the reference level and can be estimated from the difference between the sample average of some measurements and the reference level. In our case, the true values are not known and estimates of the measurement errors will be made by propagation of estimated errors (i.e. this is an uncertainty calculation).

The problem of estimating the ELA is not simply a measurement problem. Because the fan pressurization technique cannot directly measure the flow rate at 4 Pa it is necessary to extrapolate the measurable behavior to determine the desired quantity. All such extrapolations require the use of a model of the physical situation and can be considered under the rubric of *inverse problem theory* [10.]. Thus there are two broad sources of error: the errors associated with making the measurements themselves, and the model specification error.

Measurement error can be further subdivided. There are two independent measurements made: pressure and air flow. For each of these measurements there is the possibility of either precision errors or bias errors. Precision errors are treated as random errors that will change the value of a reading upon repeated measurements (i.e. noise). Fluctuations in pressure measurements caused by wind (speed and direction) variations can be treated as a precision error for fan pressurization measurements.

Wind is probably the most pernicious source of experimental error in field situations because it can cause both precision and bias errors. Modera and Wilson[11.] have shown that increasing wind speed both increases the uncertainty of the estimate and can cause a (downward) bias in that estimate. They also consider some techniques for reducing these errors. Some of these issues will be considered in following sections.

Bias errors are errors in which the reading varies in a fixed, but unknown manner from the true value such as from calibration errors (i.e. systematic errors).

Bias errors will not affect the reading for a given experimental situation and, therefore, cannot be estimated from the measurement. A common bias error in fan pressurization is non-linearity associated with the pressure measurement devices. It is possible, to estimate some kinds of bias error such as variations from instrument to instrument by using intercomparison procedures such as ASTM E691-79 [12.]. Murphy, Colliver and Piercy [13.] have reported on such an intercomparison.

Model specification (or modelization) errors come in many forms. The analysis in E779 assumes that the air flow through the envelope can be characterized by a single indoor-outdoor pressure difference (i.e. *the* pressure is measured by a single pressure location), that the flow through the envelope is equal to the flow through the fan (i.e. *the* flow), and which is described as a simple power-law function in the pressure:

$$Q = \kappa \Delta P^n \qquad \text{(EQ 1)}$$

For brevity we shall drop the 'Δ' from in front of the pressure, remembering that the pressure, *P*, indicates a pressure difference.

The ELA can be found from the flow at the extrapolated pressure of 4 Pa:

$$ELA = \sqrt{\frac{\rho}{2P_e}} Q_e = \kappa \sqrt{\frac{\rho}{2}} P_e^{(n-1/2)} \qquad \text{(EQ 2)}$$

In an actual E779 test this value is calculated separately for pressurization and depressurization and then averaged. The procedure reduces certain kinds of uncertainties and potentially creates additional model specification errors. This report, however, will not analyze either of these effects.

Since the ELA is proportional to the flow at 4 Pa, we shall henceforth deal with that extrapolated flow and determine the uncertainty in that with the understanding that it can then be converted into ELA.

We shall treat the three types of errors[1] separately and then after [14.]Coleman and Steele (1989) based on ASME (1990) [15.] measurement uncertainty principles, we shall combine the independently calculated precision, bias, and modelization errors together:

$$\delta Q_e = \sqrt{\delta^2 Q_{precision} + \delta^2 Q_{bias} + \delta^2 Q_{modelization}} \qquad \text{(EQ 3)}$$

1. We use the notation δQ to indicate the expectation value of the accuracy (i.e. the uncertainty) with an optional subscript indicating the source of the error. The uncertainties in Equation 3 and the uncertainties that will make them up (e.g. Equation 9) should be interpreted as the 95% confidence levels (about two standard deviations). (The equations are, however, also valid if the terms were all treated as standard deviations.) The notation $\delta^2 Q$ refers to the square of this confidence level.

We shall examine each of these three terms separately, but first we must describe the sources of error from the instrumentation itself.

Pressure Measurement

In Equation 1 the pressure is treated as the independent variable. In most common forms of regression analysis, errors in the independent variables are ignored; unfortunately we cannot ignore them here.

Weather-induced effects can cause significant errors in the measurement of the pressure, but in their absence there can still be biases in the measurement due to non-linearities in the gauge or calibration errors. The most commonly used pressure measurement device, the magnetically-coupled mechanical gauge, is known to have a significant non-linear response as well as hysteresis and sticking problems. Normally, however, this systematic error is within the specifications of the standard, (i.e. within 2.5 Pa), but such a systematic error can have profound effects. The size of these biases are likely to vary over the range of the measurement. The electronic pressure transducers sometimes used, do not suffer from these problems and can be calibrated to a much higher level of intrinsic accuracy.

Steady wind and temperature difference can cause the pressure drops across different parts of the envelope to vary; thus causing the model assumption of a single representative pressure to be violated. If the “preferred test conditions” are met then this violation should be less than about 4 Pa. Furthermore, the standard requires that this violation be held to less than 10% of the test pressure. It is doubtful, however, if this requirement is ever verified in the field. Slow changes in these steady weather conditions can manifest themselves as zero drift in the pressure measurement (at zero air flow); otherwise this error is independent of the size of the measured pressure.

The most noticeable error in the pressure measurement is the fluctuation of the reading caused by variations in the wind speed. According to the standard these fluctuations must be included in the 2.5 Pa and 10% of reading limits also. It is difficult (and probably rarely accomplished) to meet the 10% specification at the lowest pressure stations[1]. Some researchers are accomplishing it, however, by using an electronic transducer and time averaging the signal. Regardless of the size of this error it can be treated as being independent of the measured pressure.

Air Flow Measurement

E779 requires that the equipment used for measuring the air flow be accurate to within 6% of average value. The standard is mute on the interpretation of this statement, but for the purposes of this report we assume the requirement is to

1. Stations refer to measurements made at specified nominal values of the house pressure. For example, E779 currently requires that air flow be measured at six pressure stations: 12.5Pa, 25Pa, 37.5Pa, 50 Pa, 62.5Pa and 75Pa.

be accurate to 6% of the reading. The most common type of blower door uses the pressure drop across a calibrated orifice plate or nozzle assembly to estimate the flow through the fan. That pressure measurement is usually made with an instrument of similar design to the one for measuring the “house” pressure above, but at a higher pressure range.

For such a door the errors caused by the weather-related effects are normally not significant, because of the higher operating range. Pressure fluctuations induced by the fan as well as the non-linearity and hysteresis effects can still cause error in the “fan” pressure measurement. Additionally, the determination of the properties of the orifice plates used with the door have uncertainties associated with them.

Other types of blower doors are occasionally used (e.g. RevolutionsPer-Minute-calibrated doors); also different manufacturers calibrate their doors differently. Whether it be an orifice door or an RPM door the percentage error is always higher at the lower end of a ‘range’ (e.g. one of the orifice plates for an orifice door). In order to avoid considering each of the possible options independently, we shall make the reasonable, but not always correct, assumption that the uncertainty in the measured flow is a constant value, independent of the pressure for any given experimental design.

ONE-POINT ANALYSIS

If our objective is to determine the flow rate through the envelope at a specified pressure, the most straightforward approach would be to directly measure it at that pressure. We can construct the measurement uncertainty for such a case as follows:

$$\frac{\delta Q_e}{Q_e} = \sqrt{\frac{\delta^2 Q_{precision} + \delta^2 Q_{bias}}{Q_{fan}^2} + n^2 \frac{\delta^2 P_{precision} + \delta^2 P_{bias}}{P_e^2}} \quad \text{(EQ 4)}$$

The second term is computed from Equation 1 and is due to the fact that uncertainty in the measured pressure implies an additional uncertainty in the desired flow because we may be measuring at the wrong pressure. Thus we include the subscript “e” on the desired value.

For such an experimental design it would not be difficult to assure that the total error (i.e. both precision and bias) in the flow could be held to 5%. Similarly, we could assume that the bias in the pressure measurement could be held to 5%, but that the precision error would be about 2.5 Pa. If we apply these limits for a high pressure (e.g. 50 Pa) we get an uncertainty of about 7%.

If, we apply these limits at a low pressure (e.g. 4 Pa), we get over a 40% uncertainty.This uncertainty does not include any modelization errors associated with the assumption of a single representative pressure difference. An alternative approach would be to measure the air flow at 50 Pa and extrapolate to 4 Pa by guessing an exponent of 2/3; the overall uncertainty, however, is not improved because of the large uncertainty of the exponent. (See *Analysis of Modelization Errors* section below for more detail).

If our objective is to measure the 50 Pa air flow, a one-point measurement variant would be sufficient. As our objective is to measure the 4 Pa air flow, we need a better experimental design than a single-point measurement (at least with the current generation of instrumentation). A second measurement point would allow an improved estimate of the exponent and, therefore, of the extrapolated flow. Since Equation 1 conventionally represents the leakage process, such a two point measurement is the minimal requirement for characterization and is worthy of a more detailed examination.

TWO-POINT ANALYSIS

In this section we will analyze the situation assuming that the air flow is measured at two pressures. These two pressures will be chosen to be representative of an applicable field experiment. That is the high pressure point is in the neighborhood of 50-75 Pa and the low pressure point would typically be about a factor of six smaller. Furthermore, we wish to consider the case in which we analyze the data to obtain an extrapolation at a yet lower pressure value (e.g. 4 Pa).

The experimental design is that the air flows (Q_H, Q_L) are measured at two pressure stations, (P_H, P_L) respectively. From these two measurements we can uniquely determine the parameters of equation 1:

$$n = \frac{\log(Q_H/Q_L)}{\log(P_H/P_L)} \qquad \text{(EQ 5)}$$

(where “log” is the natural logarithm)

$$\kappa = \frac{Q_H}{P_H^n} = \frac{Q_L}{P_L^n} \qquad \text{(EQ 6)}$$

The extrapolated flow can then be found by applying Equation 1 at the desired pressure.Using Equation 1 as the defining relation, we can determine the dependence of the extrapolated flow on the measurements for the power-law model:

$$\begin{aligned} \frac{dQ_e}{dQ_H} &= \frac{Q_e}{Q_H} \times \frac{\log(P_e/P_L)}{\log(P_H/P_L)} & \frac{dQ_e}{dP_H} &= -\frac{nQ_e}{P_H} \times \frac{\log(P_e/P_L)}{\log(P_H/P_L)} \\ \frac{dQ_e}{dQ_L} &= \frac{Q_e}{Q_L} \times \frac{\log(P_H/P_e)}{\log(P_H/P_L)} & \frac{dQ_e}{dP_L} &= -\frac{nQ_e}{P_L} \times \frac{\log(P_H/P_e)}{\log(P_H/P_L)} \end{aligned} \qquad \text{(EQ 7)}$$

From these expressions we can calculate the uncertainties in the extrapolated flow due to the different sources of error.

Analysis of Precision Errors

In this section we shall assume that there are no bias or model specification errors and analyze only for uncertainties due to random fluctuations in the measurements around their true values. For such precision errors there is no bias and therefore, no first order error terms; also it is reasonable to assume that the fluctuations in the measurements are uncorrelated in which case all of the cross-terms disappear.

The uncertainty (due to precision errors alone) in the estimated flow is thus described by the familiar quadrature formula:

$$\delta Q_e = \sqrt{\left(\frac{dQ_e}{dQ_H}\right)^2 \delta^2 Q_H + \left(\frac{dQ_e}{dQ_L}\right)^2 \delta^2 Q_L + \left(\frac{dQ_e}{dP_H}\right)^2 \delta^2 P_H + \left(\frac{dQ_e}{dP_L}\right)^2 \delta^2 P_L} \quad \text{(EQ 8)}$$

Examination of these terms for our prototypical situation (i.e. extrapolation point below the low pressure station which is a factor of six below the high pressure station, plus pressure and flow uncertainties of constant size), indicates that the uncertainty in the extrapolated flow is dominated by the low pressure point. Thus we can approximate the uncertainty by the following expression:

$$\frac{\delta Q_e}{Q_e} = \frac{\log(P_H/P_e)}{\log(P_H/P_L)} \sqrt{\left(\frac{\delta^2 Q_{precision}}{Q_L^2} + n^2 \frac{\delta^2 P_{precision}}{P_L^2}\right)} \quad \text{(EQ 9)}$$

Evaluating this expression for our prototypical values and using the uncertainty specifications gives a precision error in the extrapolated flow (and, hence, the ELA of about 27%). This uncertainty is dependent upon the pressure stations. For example, increasing the lower pressure station to about 18 Pa can reduce this uncertainty to about 20%.

Analysis of Bias Errors

In this section we shall examine the effect when bias errors alone are at work. A bias error is caused when the instrument reports a difference from the true value; this difference may be a function of the size of the measurement, but it does not fluctuate. An example would be an instrument that always read 10% high. If one knew that fact it could be corrected for. Therefore one does not know, in general, the size of the potential biases that are left after any corrections.

Although bias errors are fixed, their size (and even sign) are unknown. One might infer that the same formulas that were used for precision errors would apply, but that is rarely the case. Bias errors are usually highly correlated, especially for the same quantity. For the errors we will consider herein, we can assume that the two pairs of measurements are completely correlated, but that the biases in the flow are uncorrelated with the pressure. In which case the bias error can estimated as

$$\delta Q_e = \sqrt{\left(\frac{dQ_e}{dQ_H}\delta Q_H + \frac{dQ_e}{dQ_L}\delta Q_L\right)^2 + \left(\frac{dQ_e}{dP_H}\delta P_H + \frac{dQ_e}{dP_L}\delta P_L\right)^2} \qquad \text{(EQ 10)}$$

For most experimental designs used, reasonable calibration of the fan would imply that the bias errors associated with the fan flow would be much smaller than the bias errors associated with the pressure measurement. If we ignore the bias errors from the flow then the uncertainty becomes the following:

$$\frac{\delta Q_e}{Q_e} = \left(\frac{-n}{\log(P_H/P_L)}\right)\left(\log(P_H/P_e)\frac{\delta P_L}{P_L} + \log(P_e/P_L)\frac{\delta P_H}{P_H}\right) \qquad \text{(EQ 11)}$$

Using this formula we can see that if the pressure was consistently 10% high, for example, the extrapolated flow would be about 7% low. If the pressure gauge were non-linear such that it read 10% high at the low reading and 10% low at the high reading, then for our prototypical pressure stations the extrapolated flow would be about 15% low at an extrapolated pressure of 4 Pa.

For some types of bias errors (e.g. zero drift) the bias is a fixed size (e.g.1 Pa) in which case only the low pressure station significantly contributes towards the bias in the extrapolation. If we assume such a zero error for our prototypical case we get a 9% error in the extrapolated flow. Zero drifts can be caused by the instrumentation itself, but can also be caused by reasonably steady weather conditions that shift the reading away from the average pressure drop across the envelope.

The net error from most of these sources of bias can be approximated by just using the bias caused by the low pressure point:

$$\frac{\delta Q_e}{Q_e} = -n\frac{\log(P_H/P_e)}{\log(P_H/P_L)}\frac{\delta P_{bias}}{P_L} \qquad \text{(EQ 12)}$$

Analysis of Modelization Errors

There are a virtually unlimited sources of potential model specification errors. In any experiment there are many implicit assumptions that could be incorrect. For example one normally assumes that the density of air passing through the fan does not change during the course of the test; it could and it would make difference to the estimate, but we will not consider it.

We also assume that all of the leaks experience the same driving pressure. If the leakage were linear, violation of this assumption would not be a problem (assuming the pressure measurement represented an unbiased average). The fact that the flow exponent is not unity means that there will be an error associated with this assumption failure, which will be larger for the low pressure station. The size of this effect varies over the range of house pressures typically used. The effect can be quite large when the fan-induced pressure is not enough to dominate the weather-induced pressure everywhere on the envelope. If, however, we exclude such cases from consideration, this model specification error acts like a bias in the pressure and is normally less than about 10% of the weather-induced pressures. If we restrict the pressure range to be greater than about twice the weather-induced pressure, we can neglect this effect.

Another key model specification error that we will address is the assumption that the flow can be extrapolated using a power-law formulation. It is always suspect to extrapolate data beyond the measurement limits, unless there is strong exogenous evidence (e.g. a physical law) to suggest that the functional form of the curve is valid.

The functional form of the fan pressurization curve (i.e. Equation 1) is principally justified by empirical evidence from measurements. One of us [16.] has shown that from first principles the relationship can look like a power-law over any narrow pressure range, but that over a wider pressure range it must deviate. In fact the deviation can go in either direction (i.e. increasing or decreasing exponent), depending on the distribution and type of the leaks.

If we assume that the exponent can vary as a function of pressure[1] and that there will be a deviation between the average exponent between the two pairs of pressure stations of δn then there will be a model specification error in the extrapolation of the approximate size:

$$\frac{\delta Q_e}{Q_e} = \log\left(P_e / P_L\right) \delta n \qquad \text{(EQ 13)}$$

We have examined specific, low-pressure sets of our own data and unpublished data from Walker and Wilson[6.] in an attempt to quantify the change in exponent. Ostensibly large (e.g $\delta n = 0.1$) variations can be found. If, however, the non-linearity errors and instrumentation errors are taken into account, the only conclusion that can be drawn is the variation is not consistently larger than 0.1. For the purposes of the “Error Minimization” section we will assume half that value with the understanding that such an estimate is quite crude.

Error Minimization

If we combine (in quadrature) these three sources of error we can estimate the total uncertainty of the measurement assuming that the precision and bias errors are dominated by the low pressure station:

1. The coefficient must also vary as a function of pressure to keep the airflow continuous, but we do not need to consider this effect.

$$\frac{\delta Q_e}{Q_e} = \sqrt{\left(\frac{\log(P_H/P_e)}{\log(P_H/P_L)}\right)^2\left(\frac{\delta^2 Q}{Q_L^2} + n^2\frac{\delta^2 P}{P_L^2}\right) + (\log(P_e/P_L)\,\delta n)^2} \qquad \text{(EQ 14)}$$

where we have combined the precision and bias errors for each measurement type. If we evaluate this expression for our prototypical situation the combined error is 45%.

Given that we have an expression that allows us to estimate the combined error, we can use it to optimize the experimental design. The things we can control in the experimental design are the high and low pressure stations and to some extent the errors in the instruments. All else being assumed fixed, we can find a lower pressure station that minimizes the error by using the previous equation. The table below summarized the results of using that equation:

TABLE 1. Total Errors in Extrapolation using Two-Point Method

P_H [Pa]	$\delta Q/Q_L$	δP [Pa]	P_L [Pa]	$\delta Q_e/Q_e$	$\delta Q_e/Q_e$ ($\delta n=0$)
75	10%	4	14	38%	38%
75	10%	1	9	18%	17%
75	5%	4	19	33%	32
75	5%	1	12	13%	12%
50	10%	4	12	39%	39%
50	10%	1	8	17%	17%
50	5%	4	15	34%	34%
50	5%	1	11	13%	12%

For each of these calculations we have assumed that $n = 2/3$, $\delta n = 0.05$, $P_e = 4Pa$.

Analysis of Uncertainties in the Parameters n and κ

It is sometimes desirable to characterize the data by the two parameters of Equation 1. One can calculate the uncertainties in these parameters from the data, but must also remember that the parameters may be (and are, in fact) highly correlated. As shown in the matrix equation below,

$$\begin{bmatrix} dn \\ d\kappa \end{bmatrix} = (\log(P_H/P_L))^{-1} \bullet \begin{bmatrix} 1 & -1 \\ -\log P_L & \log P_H \end{bmatrix} \bullet \begin{bmatrix} \frac{dQ_H}{Q_H} - n\frac{dP_H}{P_H} \\ \frac{dQ_L}{Q_L} - n\frac{dP_L}{P_L} \end{bmatrix} \qquad \text{(EQ 15)}$$

the dependence of these parameters on the measured data can be used to estimate the uncertainties in the parameters from the errors in the measured data

As can be inferred from this formulation, the two parameters are highly correlated and do not, therefore, have an independently measurable value. We can demonstrate this fact by calculating the uncertainty in the two parameters assuming that the errors in the measurements are uncorrelated fluctuations (See *Analysis of Precision Errors* section.) In such a case the uncertainties are as follows:

$$\delta n = \frac{1}{\log\left(P_H/P_L\right)}\sqrt{\left(\frac{\delta^2 Q_L}{Q_L^2}+n^2\frac{\delta^2 P_L}{P_L^2}\right)+\left(\frac{\delta^2 Q_H}{Q_H^2}+n^2\frac{\delta^2 P_H}{P_H^2}\right)}$$

$$\frac{\delta\kappa}{\kappa} = \frac{1}{\log\left(P_H/P_L\right)}\sqrt{\log^2 P_H\left(\frac{\delta^2 Q_L}{Q_L^2}+n^2\frac{\delta^2 P_L}{P_L^2}\right)+\log^2 P_L\left(\frac{\delta^2 Q_H}{Q_H^2}+n^2\frac{\delta^2 P_H}{P_H^2}\right)} \qquad \text{(EQ 16)}$$

We can express the correlation with the normalized covariance between the two parameters (i.e. the cross-correlation coefficient) which is close to -1:

$$r_{\kappa,n} = -1+\varepsilon$$

$$\varepsilon \approx \frac{1}{2}\left(1-\frac{\log P_L}{\log P_H}\right)^2 \frac{\dfrac{\delta^2 Q_H}{Q_H^2}+n^2\dfrac{\delta^2 P_H}{P_H^2}}{\dfrac{\delta^2 Q_L}{Q_L^2}+n^2\dfrac{\delta^2 P_L}{P_L^2}} \qquad \text{(EQ 17)}$$

For our prototypical case, ε is about 3% indicating that the uncertainties in the two parameters are about 97% (negatively) correlated. In order to use them to calculate other uncertainties, we would have to keep track of the cross terms.

If one is using the uncertainty in the two parameters to estimate the accuracy of an extrapolation, the covariance must be taken into account or the estimate will be too large. For example. κ is equal to the flow rate at an extrapolated pressure of 1 Pa. The uncertainty in that flow is given correctly by the lower half of Equation 16 without regard to the uncertainty of the exponent.

REGRESSION ANALYSIS

E779 requires multipoint pressure sampling and a regression analysis to determine parameters κ, n of Equation 1. A regression analysis has several advantages over a two-point approach: it allows an estimation of the uncertainty (due to precision errors) from the data and, by virtue of making multiple measurements it has the potential for reducing the random errors. A general example of this is that when making multiple measurements of a single variable the standard deviation can be estimated and the error of the mean is reduced as more measurements are made.

In this section we shall examine the usefulness and uncertainties associated with the regression technique using standard approaches. The reader is directed to the literature [17.], [18.] for a discussion of regression and least-squares analysis. Regression analyses explicitly exclude effects arising from bias or modelization errors, but includes precision errors. Below we analyze a few regression designs excluding the bias and model specification errors.

Numerical Analysis

For the analyses that follow we assume that conventional blower door equipment is used, but that equipment minimally meets the specifications of each analysis. Thus, the specifications of the hardware will be different for each analysis and cannot be used to determine the optimal protocol for a given set of equipment. Rather, this section allows us to compare different standards and different potential hardware designs.

The current standard requires that measurements be made every 12.5 Pa up to 75 Pa and then analyzed with an (unweighted) linear least squares approach (using the logarithms of the variables). Since conventional blower door equipment uses orifice-type flow measurement, the 6% specification on air flow measurement accuracy will be interpreted to mean that at the lowest pressure station the air flow uncertainty will be 6%; such an assumption leads to a higher level of accuracy at higher pressure stations. We also assume that the exponent of the leaks is 0.65 (compared with 0.5 for the orifice plate) and that the absolute accuracy of the (house) pressure is 2.5 Pa. We have done an error analysis of this approach using synthetic data with measurement errors otherwise similar to our prototypical case and found the following for the **E779 Analysis**:

$$\begin{aligned} \delta n &= 0.07 \\ \delta \kappa &= 29\% \\ \varepsilon &= 0.1\% \\ \frac{\delta Q_e}{Q_e} &= 19\% \end{aligned} \qquad \text{(EQ 18)}$$

By using an unweighted regression of the logarithms of the data, this type of analysis implicitly assumes that the uncertainty (due to precision errors) is a constant fraction of the measured value. As discussed earlier, this is not a good assumption for the pressure measurement. The net effect of this incorrect assumption is that the low point has an unduly large influence on the result of the regression. We can correct this error by weighting each point according to its estimated accuracy. The weights are derived from the total uncertainty of each measured point and can be derived from the “ONE-POINT ANALYSIS” (The weight is the inverse square of Equation 4.) Doing so downweights the low points appropriately. we call this the ***weighted E779 Analysis:***

$$\begin{aligned} \delta n &= 0.04 \\ \delta \kappa &= 18\% \\ \varepsilon &= 0.3\% \\ \frac{\delta Q_e}{Q_e} &= 12\% \end{aligned} \tag{EQ 19}$$

It is apparent that weighting the points reduces the precision error of the estimated flow. One must also be aware that by downweighting the low pressure points there could be an increase in the extrapolation error associated with model specification. It is, however, quite difficult to estimate the impact of this model specification error without a better model of how the exponent might vary with pressure.

The Canadian General Standards Board (1986) has a standard analogous to ASTM E779 in which only depressurization is done and for which the pressures range from 15 to 45 Pa in 5 Pa steps; the accuracy requirement on the flow is 5% rather than 6%. We can perform a similar analyses to determine the uncertainties using the **CGSB Analysis:**

$$\begin{aligned} \delta n &= 0.08,\ 0.06 \\ \delta \kappa &= 27\%, 22\% \\ \varepsilon &= 0.2\%, 0.3\% \\ \frac{\delta Q_e}{Q_e} &= 17\%, 14\% \end{aligned} \tag{EQ 20}$$

where the first number is for an unweighted regression and the second for the weighted regression. The CGSB weighted regression technique is based on standard statistical methods[19.]] to compensate for differential errors in the flow measurement only. As can be seen from the two-point analysis the uncertainty in the final answer due to the flow error is small compared to that caused by the pressure error. Our analysis uses the regression weights (as stated earlier) to include both flow and pressure error, but did use the CGSB pressure stations and instrumentation assumptions.

Since all the points in the previous analyses are a fixed pressure spacing apart, they actually are more heavily weighted towards the high pressure side for the logarithmic analysis. An alternative approach is one in which one attempts to overcome this problem by logarithmically spacing the points (at 10, 14.3, 20.5, 29.3, 41.9 and 60 Pa) and by weighting the points using an estimate of the measurement uncertainty. Using synthetic data for the same assumptions as above for the E779 analysis, we find the following for the **Log-spaced Analysis:**

$$
\begin{aligned}
\delta n &= 0.08,\ 0.05 \\
\delta \kappa &= 28\%, 19\% \\
\varepsilon &= 0.3\%, 0.6\% \\
\frac{\delta Q_e}{Q_e} &= 17\%, 12\%
\end{aligned}
\qquad \text{(EQ 21)}
$$

It has been suggested that a reasonable compromise between these two approaches might be to use equally spaced points from 10 to 60 Pa, but to include the appropriate weighting the in the analysis. For such an experimental design our analysis yields the following:

$$
\begin{aligned}
\delta n &= 0.05 \\
\delta \kappa &= 21\% \\
\varepsilon &= 0.4\% \\
\frac{\delta Q_e}{Q_e} &= 13\%
\end{aligned}
\qquad \text{(EQ 22)}
$$

Because the percentage error (i.e. the weights) change substantially over the range of measurement, it is usually superior to use a weighted regression when analyzing fan pressurization data. As these examples demonstrate the precision error is reduced because the points contributing more to the uncertainty are weighted less. Although not apparent from the results, the same can be true for some types of bias errors.

As discussed in the "TWO-POINT ANALYSIS" section bias and model specification errors can come in many guises. Because bias errors can be highly correlated between measurements, the multipoint advantages of a regression may not reduce their impact. Although, in general, the regression analysis will give larger bias errors than an analogous two-point analysis, we will make the same approximations and use the same expression, Equation 12, to estimate the bias errors. Similarly, we can assume that modelization errors can be approximated by Equation 13 Accordingly, for each of the regression analyses above, terms must be added to the uncertainties to account for the bias and model specification errors.

IMPROVING THE TEST METHOD

The sections above have indicated the sources and ranges of the errors that affect the test method for determining the extrapolated flow at 4 Pa. This section discusses ways of improving the method to decrease the uncertainty.

Reducing Precision Errors

The use of multiple measurements, as in a regression analysis can reduce the uncertainty of the result, due to precision errors. This uncertainty can also be reduced by increasing the precision of the measurement itself. Such precision increases can either come from improved instrumentation or a reduction or limitation on the exogenous noise sources through improved experimental design.

Weather and specifically wind play an important role in the precision of the house pressure measurement, especially at the low end of the measurement range. Wind pressures around buildings are quite turbulent and it is reasonable to anticipate that the variations of these pressures will be a substantial fraction of their mean value. Limiting the mean wind conditions of the test is one way to reduce precision errors, but it also reduces the applicability and, therefore, usefulness of the measurement procedure.

Noise can also be reduced by making time-averaged measurements for each pressure station. This can be accomplished by making multiple measurements and averaging as part of the analysis or by having the instrumentation average as part of making the measurement. For example, six measurements of a single pressure can reduce the precision error from 2.5 Pa to 1 Pa. Although it is normally the pressure measurement that contributes the most to the uncertainty, the increase in precision is equally applicable to the flow measurements.

Multipoint vs. Two-Point Testing

Given that we can use the various techniques described above to improve the precision of the measurements, multipoint testing (i.e. regression analysis) is, theoretically, inferior to two-point testing for extrapolating to lower pressures[1]. It is, however, a more robust method because it can bring to light systematic errors not anticipated in the design such as instrumentation failures, changes in the experimental set-up (e.g. changes in leakage behavior caused by the pressure), and unusual variations in the parameters.

Optimal design would then include a small number of pressure stations to be (optionally) used in a regression analysis[2]. The precision of the measurement at each pressure station should then be used to weight the regression. It is important to recognized, however, that the uncertainty in the extrapolation will still be heavily dependent on the properties of the lowest pressure point(s).

1. It can be shown the least uncertainty can be achieved when all measurements are concentrated at the end points rather than distributed over the range.

2. The extra points between the end-points can cause the extrapolation to get worse if there are certain types of systematic errors in operation; thus the term “optionally”

Location of Low-Pressure Station

The optimal selection of the low-pressure station is a trade-off between measurement and model specification errors. The precision and (especially) bias considerations of the pressure measurement would suggest that a higher value of the pressure station would provide better estimates. The model specification error due to a non-constant exponent would suggest a lower value. Table 1, “Total Errors in Extrapolation using Two-Point Method,” demonstrates these trade-offs for a particular set of values.

In addition to these considerations it is important that other types of systematic errors be avoided. For example, if the low pressure station were too low, the model specification error associated with the single pressure difference assumption would have to be considered.

Location of High-Pressure Station

As Table 1, indicates the uncertainty for that set of assumptions is not highly dependent on the location of the high-pressure station for fixed low pressure and extrapolated pressure values. There are, however, a few other concerns that one should consider in making this selection: the range of measurement and compatibility with other uses.

The range of pressure measurements can be expressed by the ratio of the highest pressure station to the lowest. All else being equal the larger this ratio is the better is the determination of the exponent and, hence, the extrapolated flow. A large ratio, however, implies that the measurement equipment needs a large dynamic range. Since increasing the dynamic range of an instrument usually increases its error, it is important not to make the ratio too big. For the typical instruments used, values of the ratio in the 3-5 range should work well, but a better approach would be to reoptimize for specfic circumstances.

Many practitioners use blower doors to measure the flow at 50 Pa as a construction quality indicator. As discussed in “ONE-POINT ANALYSIS” the accuracy and precision demands for this purpose are much less than for our purposes. Therefore, it might be useful to have one of the pressure points be at 50 Pa.

Other ASTM Test Methods, such as E283 and E783 [5.], suggest that 75 Pa should be used for the leakage testing of components. Although this value is not required, but only suggested, in these standards, similar considerations apply as above.

Reducing Bias and Modelization Errors

Bias errors can be reduced by appropriate choice of instrumentation and experimental design. Instruments should be chosen whose intrinsic bias (caused by such things as non-linearity, hysteresis, etc.) is smaller than the bias due to calibration error and the necessary precision of the measurement. Once the instrument bias is sufficiently reduced, the bias in the pressure measurement is primarily due to the weather conditions. To reduce the bias effect of the weather a few changes in experimental technique can be made.

The wind spectrum has many frequency components. The highest ones will behave as noise and be part of the precision error. Lower frequencies (i.e. those on the order of the time of the measurements) will appear as drift in the reading made with no flow through the fan (i.e the effective or relative zero). Therefore, it is important to measure the effective zero before and after each measurement. The pairs of zero measurements can be used both to correct the measurement and to estimate the size of the zero drift bias. Physical pressure averaging devices such as those used with the CGSB[20.] standard, can help minimize this bias error as well as precision errors.

A steady wind causes a modelization error because it induces differential pressures on the faces of the envelope. These pressures must be kept significantly smaller than any of the pressure stations to avoid introducing another error. As long as the peak variation from building face to building face is less than half the pressure station, the effect can be ignored, especially if the both pressurization and depressurization tests are made. The *preferred conditions* of the current ASTM standard E779-87 should normally insure this.

AN IMPROVED MEASURMENT PROTOCOL

In this section we propose an improved measurement procedure based on the analyses above. We include instrumentation specifications, experimental procedures and analysis methods to be used. These recommendations combine both theoretical arguments with practical considerations and thus may not be unique.

Instrumentation Specifications

The flow measuring device must be unbiased to within 2%; that is, all biases including calibration errors and non-linearities must be no more than 2% of the reading. The intrinsic precision error of the instrument should be no more than 5% of reading; that is, any internally generated (electronic or mechanical) fluctuations may be no more than 5% of the reading.

The pressure measuring device must be unbiased to within 5% of reading, and also to within 1 Pa of the reading, whichever is more restrictive. Similarly, the intrinsic precision error must be no more than 5% of reading or 1 Pa.

Procedure

Because of the need for precision higher than is usually afforded by a single measurement, provision must be made to estimate the mean of both the pressure and the air flow rate at a pressure station and to estimate the error of that mean.

The airflows are to be measured at 4 pressure stations 10, 15, 25, 50 Pa.

At each pressure station sufficient data must be taken to assure that the error the mean is no more than 2% of the mean air flow reading and 5% of the mean pressure reading.

Before and after each pressure station dataset the zero pressure must be measured to a precision of 5% of the pressure station. The pressure station reading should be corrected by the average of these two values. The corrected mean value of the pressure must be within 10% of the desired station pressure. The difference between the two zero measurements must be within 5% of the station pressure.

Analysis

The data is to be analyzed using a weighted regression technique. We have used synthetic data with the specifications of this section to determine the expected (precision) uncertainties for both the unweighted and weighted techniques:

$$\begin{aligned} \delta n &= 0.02,\ 0.01 \\ \delta \kappa &= 7\%, 5\% \\ \varepsilon &= 0.4\%, 0.7\% \\ \frac{\delta Q_e}{Q_e} &= 4\%, 3\% \end{aligned} \qquad \text{(EQ 23)}$$

The uncertainty of the final result has been significantly reduced (compared to the E779 standard method, Equation 18), primarily because the measurement uncertainties have more stringent specifications. The advantages of weighting the regression still exist, but are not as apparent due to the improved measurement accuracy.

DISCUSSION AND CONCLUSIONS

Because we are interested in extrapolating an apparent power-law curve below the lower limit of the measurements, an analysis of uncertainties is dominated by the low-end behavior. The precision, bias and model specification errors must all be minimized.

The precision errors are mostly caused by the environmental variations during the test. For any given set of circumstances the precision error can be minimized by averaging time series measurements at single pressure station. The number of measurements required to meet a particular precision target will depend on the environmental conditions and other sources of noise. Increasing the number of points in the regression analysis is another way of reducing the overall precision error.

Bias errors cannot usually be reduced with multiple measurement. Rather the specifications and calibration of the instrumentation and the experimental protocols must be optimized. For example, in order to extrapolate to 4 Pa it is important to keep the pressure bias below 1 Pa. Because it may be difficult to keep the environmentally-induced biases below such a level, it is important to make sure that the instrumentation itself has a bias much smaller than that. Thus, instrumentation exhibiting significant zero drift, non-linearity or hysteresis must be avoided.

Modelization errors principally affect measurements or extrapolations made near the range of naturally occurring pressures. If measurements are made at too low a pressure--even if the measurements are quite accurate--there may be a error due to the non-linearities of the leaks. The procedure recommended above, for example, could be used to a wind speed of 3 m/s and a temperature difference of 30 K without inducing that type of modelization error. Similarly if the measurements are made at too high a pressure there may be a significant uncertainty due to the departure from a true power law.

There does not currently exist a body of sufficiently well characterized data that would allow an empirical determination of the size of these modelization errors. Typical blower door technology is unable to make the necessary measurements, but a thorough understanding of the low pressure behavior of the leakage function is necessary to improve the accuracy of the technique over the limits indicated herein. Such an understanding can only be gained by making detailed, high accuracy measurements across many building types; such measurements may require or lead to the development of novel leakage measurement techniques.

Within the confines of our current knowledge and fan pressurization technology, uncertainty can be optimized by appropriate choices for the pressure stations. The most striking conclusion of this study is that the accuracy of current fan pressurization tests are limited by the uncertainties associated with measuring the lowest pressures. Uncertainty associated with the extrapolation would suggest that measurements be made at low pressures, while the need to minimize percentage uncertainties suggest the measurements be made at high pressures. Equipment limitations suggest the range of pressures should be small, while statistical arguments suggest that a large pressure range might be better. Rules of thumb suggest that the low pressure point should be in the range of 10-20 Pa, the high pressure point should be in the 40-60 Pa range and the range should be between a factor of three and five. These rules represent trade-offs that involve some judgement based on typical equipment specifications and noise sources; other ranges may also prove useful in some circumstances.

There are many factors we did not address in how standard E779 is or should be constructed. These factors include issues relating to the preparation of the envelope (e.g. the sealing of vents), whether pressurization or depressurization or both should be done, the effects of internal resistance to air flow, the changes in temperature and the related effects caused by density changes, and errors caused by specific blower door designs. While all of these issues are potentially important and must be addressed, they are beyond the scope of this report.

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NOMENCLATURE

TABLE 2. Nomenclature

κ	Leakage Coefficient [m^3/s-Pa^n]
n	Flow Exponent [-]
P, ΔP	Outdoor-Indoor Pressure [Pa]
Q	Air Flow [m^3/s]
ρ	Density of Air [1.2 kg/m^3
r	Correlation Coefficient [-]
Subscripts:	*indicate*
bias	bias error
e	value at extrapolated pressure
modelization	modelization error
precision	precision error
fan	reading from blower door
H	High pressure point
L	Low pressure point